SOIL AGGREGATION UNDER DIFFERENT MANAGEMENT SYSTEMS[1]

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SUMMARY

Considering that the soil aggregation reflects the interaction of chemical, physical and biological soil factors, the aim of this study was evaluate alterations in aggregation, in an Oxisol under no-tillage (NT) and conventional tillage (CT), since over 20 years, using as reference a native forest soil in natural state. After analysis of the soil profile (cultural profile) in areas under forest management, samples were collected from the layers 0-5, 5-10, 10-20 and 20-40 cm, with six repetitions. These samples were analyzed for the aggregate stability index (ASI), mean weighted diameter (MWD), mean geometric diameter (MGD) in the classes > 8, 8-4, 4-2, 2-1, 1-0.5, 0.5-0.25, and < 0.25 mm, and for physical properties (soil texture, water dispersible clay (WDC), flocculation index (FI) and bulk density (Bd)) and chemical properties (total organic carbon - COT, total nitrogen - N, exchangeable calcium - Ca^{2+}, and pH). The results indicated that more intense soil preparation (M < NT < PC) resulted in a decrease in soil stability, confirmed by all stability indicators analyzed: MWD, MGD, ASI, aggregate class distribution, WDC and FI, indicating the validity of these indicators in aggregation analyses of the studied soil.

Index terms: aggregation indices, aggregate size classes, total organic carbon.

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RESUMO: *AGREGAÇÃO DE SOLO COM DIFERENTES MANEJOS*

Considerando que a agregação reflete na interação dos fatores químicos, físicos e biológicos dos solos, o objetivo deste trabalho foi avaliar a agregação de um Latossolo Vermelho distroférrico sob plantio direto (PD) e preparo convencional (PC) implantado há mais de 20 anos, utilizando-se como referência do estado natural uma mata nativa (M). Após análise do perfil de solo pelo método do perfil cultural nas áreas sob manejo e mata, foram coletadas amostras nas profundidades de 0-5, 5-10, 10-20 e 20-40 cm de profundidade, com seis repetições. A partir dessas amostras, foram determinados o índice de estabilidade dos agregados (IEA), o diâmetro médio ponderado (DMP), o diâmetro médio geométrico (DMG) e as classes de diâmetro >8, 8-4, 4-2, 2-1, 1-0,5, 0,5-0,25 e < 0,25 mm, além das determinações físicas (granulometria, argila dispersa em água - AD, índice de floculação - IF e densidade do solo - Ds) e químicas (carbono orgânico total - COT, nitrogênio total - N, cálcio trocável - Ca^{2+} e pH). Os resultados indicaram que o aumento da mobilização do solo (M < PD < PC) resultou em diminuição da sua estabilidade, medida por meio de todos os indicadores de estabilidade analisados: DMP, DMG, IEA, distribuição de classes de agregados, AD e IF, concluindo-se pela validade deles em estudos de agregação do solo considerado.

Termos de indexação: índices de agregação, classes de agregados, carbono orgânico total.

INTRODUCTION

Intensive soil use and systematic implementation of inappropriate agricultural practices, such as excessive topsoil preparation and high losses of crop residues and soil by erosion, alter the original soil properties (Carpenedo & Mielniczuk,1990), affecting the organic matter content (Pereira et al., 2010; Primo et al., 2011) and degrading the soil structure, as evidenced by increased soil density and reduced aggregate size, macroporosity, final infiltration rate and plant root development (Llanillo et al., 2006; Reichert et al., 2009; Ferreira et al., 2010; Tavares Filho & Tessier, 2010; Cunha et al., 2011).

The adoption of cropping and management systems that conserve the soil and continually introduce fresh organic residues is fundamental to preserve a good soil structure (Lal & Greenland, 1979; Calegari et al., 2006; Tavares Filho & Tessier, 2010), with lower bulk density and better macro and micropore distribution (Tavares Filho et al., 2001; Schaffrath et al., 2008; Luciano et al., 2010).

The vegetation and organic residues protect the surface layer aggregates against degradation by raindrop impact and abrupt variations in moisture content, and also represent a source of energy for the microbial activity, which produces valuable byproducts that act as agents for aggregate formation and stabilization (Harris et al., 1966; Calegari et al., 2006; Salton et al., 2008; Coutinho et al., 2010).

According to Castro Filho et al. (1998), the no-tillage system with accumulation of plant organic residues on the surface improves aggregation by increasing organic carbon levels in the topsoil, raising the percentage of aggregates > 2.00 mm, as observed by Beutler et al. (2001), and distributing the capillary system carrying water in the arable layer more evenly, resulting in higher infiltration and storage for longer periods.

The continually interacting physical, chemical and biological factors, variations in crop yields over time, the relationship between soil formation and loss by erosion, the accumulation or loss of organic matter and the production of entropy (Addiscott, 1995; Reicosky et al., 1995) can therefore be used to determine whether an agricultural soil is stable, improving or deteriorating.

Bearing in mind that the management system used changes the dynamic equilibrium of the soil, the aim of this study was to assess the effects of management systems established for over 20 years on the aggregation of a dystrophic Red Oxisol.

MATERIAL AND METHODS

The experimental area is in the municipality of Bela Vista do Paraíso, Paraná State, Brazil (22° 57'S, 51° 11' W). The soil is classified as a dystroferric Red Oxisol (Brazilian classification: Latossolo Vermelho distroférrico) with a clay content of 670 - 740 g kg^{-1} (Table 1). The primary vegetation consists of semi-evergreen tropical forest and the climate classification is humid subtropical, with average maximum and minimum temperatures of 22 and 18 °C. Average annual rainfall is 1,850 mm and average sunlight 7 h day^{-1} (Caviglione et al., 2000).

The management systems evaluated were no-tillage and conventional tillage, established 20 years earlier. Soil under native forest was used as a reference for the natural structural state of the soil.

Profile descriptions for the soils under different management systems and native forest were prepared

Table 1. Results of granulometric analysis under the two management systems and native forest at four soil depths

Depth	Forest			No-tillage			Conventional Tillage		
	Clay	Sand	Silt	Clay	Sand	Silt	Clay	Sand	Silt
cm	g kg^{-1}								
0-5	670	130	200	740	140	120	700	120	180
5-10	680	140	180	730	160	110	700	130	170
10-20	690	130	180	730	160	110	710	120	170
20-40	700	170	130	730	160	110	740	130	130

using the crop profile method (Tavares Filho et al., 1999; Neves et al., 2003) to identify structural discontinuities, i.e. layers with structures that are visibly different, referred to as "morphologically homogeneous anthropic layers" (MHAL). The identification of these MHAL layers in agricultural areas was based on how human activity had influenced the profile, i.e. the effects of using machinery, presence/absence of fine earth, the shape, arrangement, size and cohesion of aggregates and clumps, visible compaction, etc. In the area under native forest, the same features were detected, with the exception of the effect of machinery. To clarify the presentation of the results, the following symbols are used to describe the MHAL layers: Fr = free; C = continuous, Cr = cracked, pt = small clumps; μ = high visible porosity, Δ = compact clumps with no visible porosity, Δμ = compact clumps with little visible porosity, Δμ/Δ = (transition)-compact clumps with some visible porosity.

After identifying the MHAL layers, five disturbed and five5 undisturbed soil samples were collected from each management system and the native forest (layers 0-5, 5-10, 10-20 and 20-40cm) for chemical and physical analysis, except soil density for which samples were collected from the layers 0-10, 10-20 and 20-40cm. The pH in $CaCl_2$ 0.01 mol L^{-1} and Ca^{2+} were determined using the method described by Embrapa (1997), total organic carbon (TOC) using the dry combustion method (Nelson & Sommers, 1986) in a LECO® CR-412 Carbon Analyser, and total nitrogen (N total) by the micro-Kjeldahl system (Embrapa, 1997). Soil bulk density (Bd) was obtained using a volumetric ring with internal volume of 50 cm^3. Water-dispersed clay (WDC) was evaluated using the pipette method described by Day (1965), with no dispersant. The flocculation degree was obtained as described in Embrapa (1997).

Aggregate stability was determined by the method of Yoder (1936), modified by Castro Filho et al. (1998). After sampling the soil material was passed through a 19mm mesh sieve. In the laboratory, the assessments were repeated three times using 8.0, 4.0, 2.0, 1.0, 0.5 and 0.25 mm mesh sieves. The soil retained in each sieve was quantified, including aggregates below 0.25 mm, subtracting the sum of the weight of the other aggregate classes from the total dry sample weight. In this way, six aggregate classes with measured sizes of 13.5, 6.0, 3.0, 1.25, 0.375 and 0.125 mm were separated. The means of the data obtained were used to calculate the mean weighted diameter (MWD), mean geometric diameter (MGD) and aggregate stability index (ASI), according to Castro Filho et al. (1998). For the ASI calculation, any sand was ignored.

Statistical analysis was run on the SAS statistics program (SAS, 1997). The data were analyzed taking the laboratory replications for soil aggregation and field replications for density and chemical analysis into account. The output data were grouped according to depth and the means subjected to the Tukey test at 1 and 5 %.

RESULTS

Visual assessment of soil morphology

Figure 1 is diagrammatic representations of the cropping profiles for the two management systems evaluated and native forest (reference).

The soil under native forest (Figure 1) had the typical characteristics of a Red Oxisol, structurally organized in small stable granular aggregates, forming a rich network of pores by aggregate stacking, evidenced in the large portion of the profile organized as Cm. Intra-aggregate porosity occurs in the form of channels, mainly produced by biological activity and root growth. In cultivated soils (Figure 1), these granular aggregates occur only at depths below 50 cm, showing that there is no human interference below this depth.

Under NT (Figure 1), there was a predominance of cracked structures (Cr) whose main characteristic is the separation of clumps resulting in crack porosity, predominantly, through which most roots grow. The profile consisted of compact aggregates with the presence of CrΔ and CrΔμ layers down to 53 cm. Along the sowing furrow, CrΔμ/Δ structures were found as well, in contrast to the CrΔ lateral structure at the same depth. The presence of CrΔμ/Δ structures along the sowing furrow as opposed to a continuous lateral CrΔ structure must be due to the intensive development of the root systems of maize grown in the region. The effect of root systems, especially of grasses, can lead to the transformation of more compact aggregates into more rounded, rougher, less compact aggregates. Similar results were reported by Correchel et al. (1999).

Under CT (Figure 1), continuous structures are predominant (C), forming a fairly homogeneous volume, with a solid appearance, making it difficult

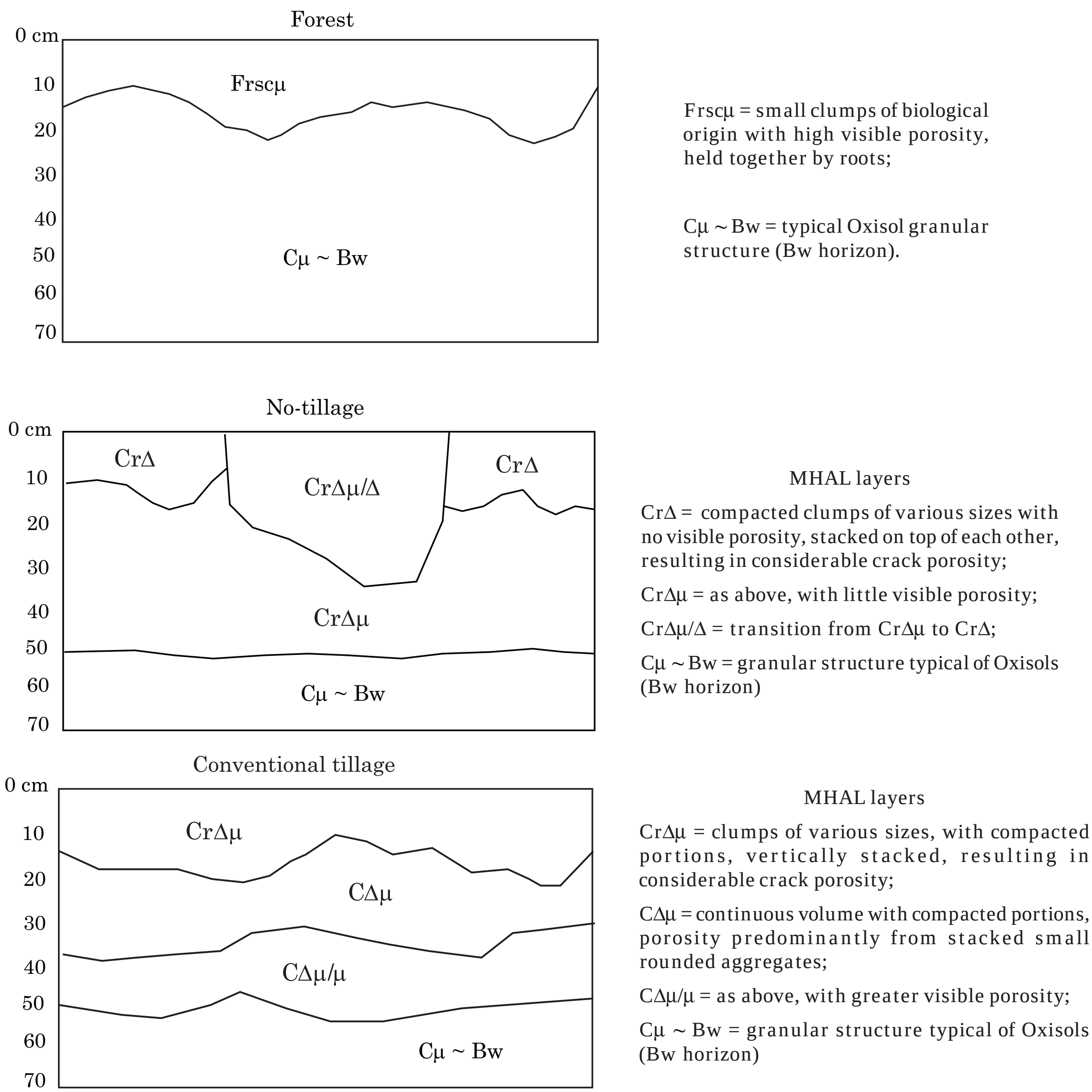

Figure 1. Diagrammatic representation of morphologically homogeneous anthropic layers (MHAL) under forest (a), no-tillage (b) ande conventional tillage (c).

to individualize the clumps. Volumes of CΔμ soil were found at depths between 21 and 57 cm. The cracked structure (CrΔμ) was present from the soil surface to a depth of 21 cm.

These results are in line with Neves et al. (2003), Benito et al. (2008), Domingos et al. (2009) and Tavares Filho & Tessier (2009, 2010) and show the differences in soil structure of the two management systems. Conventional tillage of this area with a plow and one or two leveling disk harrows and no-tillage cultivation induced considerable changes in the soil structure between 0 and 0.5 m in comparison to the soil under native forest, with increasingly compacted structures and root growth predominantly in the cracks.

Aggregate stability index and soil physical traits:

Table 2 shows the results for mean weighted diameter (MWD), mean geometric diameter (MGD) and the aggregate stability index (ASI), distribution of aggregate size classes (Table 3) and water-dispersed clay (WDC), clay flocculation index (FI), Ca^{2+}, pH, organic C, C/N ratio and total N (Table 4), for the two management systems at four soil depths.

In an overall analysis of the results, it was seen that MWD, MGD and ASI decreased in all layers (Table 2) as soil disturbance increased (F > NT > CT), confirming the validity of these stability indicators in this study, i.e. soil stability was inversely proportional to soil disturbance.

Taking the higher-diameter classes (from > 8 mm to 2-1 mm) (Table 3), the percentage of larger aggregates is higher for the least disturbed soil, in the following order: F >NT > CT. For smaller size classes, as from 0.50-0.25 mm the reverse occurred, with a higher quantity of aggregates as soil disturbance increases (CT > NT > F). This means that soil disturbance reduced the proportion of larger clumps, increasing the proportion of smaller clumps, i.e. reduced aggregate size, corroborating the results in table 2.

The water-dispersed clay (WDC) and clay flocculation index (FI) (Table 4) showed a general tendency of rising WDC and decreasing FI when the soil is disturbed (F >NT > CT), in line with the results in tables 2 and 3.

Therefore, increased soil disturbance resulted in a drop in soil stability (F >NT > CT), measured by all tested stability indicators: MWD, MGD, ASI, distribution of aggregate classes, WDC and FI, in all layers. In other words, despite a small reduction in this effect in the deeper layers, the phenomenon was detectable down to the deepest level studied, at 40 cm.

With regard to the C/N ratio, the means were highest under NT, of all management systems and at all depths analyzed. Forest (F) had the highest average in the 0-5 cm layer only. The means under CT were lowest in the layers 5-10 and 20-40 cm (Table 4).

Table 2. Effect of the soil management system on mean weighted diameter (MWD), mean geometric diameter (MGD) and aggregate stability index (ASI)

Management system(1)	Depth	MWD	MGD	ASI
	cm	mm		%
F		3.06 A(2)	1.35 A	89.19 A
NT	0-5	2.79 B	1.10 B	83.21 B
CT		1.64 C	0.53 C	60.62 C
CV (%)		5.48	4.53	1.23
F		3.24 A	1.47 A	90.78 A
NT	5-10	2.78 B	1.18 B	87.05 B
CT		1.95 C	0.70 C	71.19 C
CV (%)		3,05	4.03	1.35
F		3.07 A	1.34 A	88.67 A
NT	10-20	2.34 B	1.01 B	83.80 B
CT		1.71 C	0.63 C	69.41 C
CV (%)		7.26	6.08	1.97
F		3.21 A	1.43 A	90.23 A
NT	20-40	2.18 B	0.89 B	80.58 B
CT		1.78 C	0.66 C	68.59 C
CV (%)		4.71	5.07	1.37

(1)Management systems: F: forest; NT: no-tillage; CT: conventional tillage. (2)Means followed by the same letter in each column for each layer did not differ statistically by the Tukey test at 5 %.

Figure 2 shows that soil densities in the NT and CT systems did not differ significantly from each other, but did differ from F, where average densities were lowest.

The TOC values in figure 3 show that there was no significant difference between the CT and NT systems, but both differed from F. This similarity between NT and CT may be attributable to the high coefficient of variation (CV%) among the three systems (45.68 %).

However, when the means were tested, the only statistical difference ($p<0.01$) was between the two management systems, NT and CT, with the highest average in the 0-5 cm layer of the NT system (Table 5), with a CV of 7.84 %. In the lower layers (5-10, 10-20 and 20-40 cm) there were no significant differences.

According to Harris et al. (1966), Arshad et al. (1996), Beutler et al. (2001) and Ramos et al. (2010), the use of physical indicators is an important strategy for assessing soil aggregation (sustainability) of the management systems. Thus, the results presented in this study show that the combined effect of a number of aggregating substances and mechanisms responsible for the process of forming and stabilizing aggregates, such as the soil texture, the carbon and iron content as well as the management system, can contribute to achieve high values for MWD, MGD and ASI.

Carpenedo & Mielniczuk (1990) reported that the separation of clumps can be the result of particle aggregation under the pressure exerted by the machinery used, increasing the MWD of the soil aggregates under no-tillage due to compression forces, as in the case of the cracked structure (F) found mainly in the no-tillage system (Figure 1). This could be related to the higher MWD, MGD and ASI values under no-tillage (Table 2).

In our study, the soil aggregation indicators performed well in detecting the effect of different management systems, i.e. lower average values for MWD, MGD and ASI in the 0-5 cm layer in comparison to 5-10 cm (Table 2) occur because of the presence of a small layer of freely structured soil with small loose aggregates and fine earth in the NT and CT systems (visual assessment of soil morphology). This layer appeared as a result of tilling the topsoil with machinery, especially leveling disk harrows in the CT system, and, of sowing (blade in front of seed and fertilizer deposition disks) in the NT system, above all in the case of wheat which, for being more densely spaced, results in greater soil disturbance.

The values for MWD, MGD and ASI were highest under native forest, for all layers (Table 2). This was related to higher organic C levels (Figure 3), which have a marked effect on soil aggregation.

Of the management systems studied, the aggregation indicators (MWD, MGD and ASI) were highest in NT, in all layers analyzed. The highest indicator values were found in the 5-10cm layer under NT (Table 2), although TOC was higher in the 0-5 cm layer.

The fact that lime was applied as top dressing in the NT system could have resulted in substantial

Table 3. Distribution of aggregate size classes as a function of management system and soil depth

Management system(1)	Depth	Aggregate size classes (mm)						
		>8	8-4	4-2	2-1	1-0.50	0.50-0.25	<0.25
	cm	%						
F		11.0 A(2)	9.60 A	17.3 A	16.8 A	18.0 B	17.8 B	9.40 C
NT	0-5	10.5 A	8.72 A	14.1 B	12.9 B	21.3 A	17.7 B	14.7 B
CT		4.64 B	5.53 B	10.6 C	6.03 C	13.9 C	26.0 A	33.2 A
CV (%)		11.8	7.59	4.33	4.45	3.49	3.39	4.66
F		12.2 A	9.67 A	18.5 A	16.7 A	19.8 B	15.3 C	7.92 C
NT	5-10	9.7 A	8.89 A	16.4 B	13.9 B	21.1 A	18.8 B	11.3 B
CT		6.74 B	5.49 B	11.8 C	10.7 C	15.1 C	25.5 A	24.6 A
CV (%)		6.85	10.26	5.01	4.90	3.51	4.11	6.88
F		11.3 A	9.5 A	17.3 A	16.0 A	18.9 B	17.0 B	9.85 C
NT	10-20	7.33 B	7.12 B	17.2 A	13.2 B	21.7 A	19.2 B	14.3 B
CT		4.76 C	5.63 C	11.8 B	8.12 C	15.9 C	27.9 A	25.7 A
CV (%)		15.1	9.01	7.34	8.68	3.60	5.30	8.81
F		11.9 A	10.0 A	18.2 A	15.8 A	18.7 B	16.9 C	8.39 C
NT	20-40	6.72 B	6.34 B	14.3 B	13.7 B	21.8 A	20.3 B	16.9 B
CT		5.13 B	5.39 B	11.9 C	9.78 C	20.0 A	21.4 A	26.4 A
CV (%)		10.1	7.05	3.76	3.79	3.64	5.57	5.97

(1)Management systems: F: forest; NT: no-tillage; CT: conventional tillage. (2)Means followed by the same letter in each column for each layer did not differ statistically by the Tukey test at 5 %.

Table 4. Mean values for water-dispersed clay (WDC), clay flocculation index (FI), calcium (Ca^{2+}), pH, total organic C, C/N ratio and total N for different management systems

Management system(1)	Depth	WDC	FI	Ca^{2+}	pH	TOC	C/N	N total
	cm	g kg^{-1}	%	$cmol_c$ dm^{-3}		g kg^{-1}		g kg^{-1}
F		116 A(2)	82.7 A	21.9 A	6.5 A	72.0 A	9.3 A	7.7 A
NT	0-5	122 A	83.5 A	7.25 B	6.1 B	23.5 B	10.2 A	2.3 B
CT		135 A	80.7 A	4.7 B	5.2 C	18.5 B	7.4 B	2.5 B
CV (%)		31.27	6.53	20.61	2.85	45.68	6.46	37.31
F		107 A	84.3 A	16.8 A	6.6 A	47.4 A	8.6 B	5.5 A
NT	5-10	141 A	79.9 A	6.8 B	5.8 B	19.4 B	9.5 A	2.0 B
CT		156 A	78.6 A	4.3 C	4.9 C	17.9 B	7.6 C	2.4 B
CV (%)		48.85	11.64	7.03	5.17	31.75	5.23	27.35
F		123 A	82.2 A	13.9 A	6.5 A	31.2 A	7.6 B	4.1 A
NT	10-20	146 A	79.4 A	6.6 B	5.8 B	17.1 B	9.1 A	1.9 B
CT		157 A	78.5 A	4.3 C	5.0 C	16.1 B	7.4 B	2.2 B
CV (%)		41.55	10.43	16.94	4.82	13.25	7.54	19.11
F		70 B	90.0 A	12.5 A	6.3 A	30.4 A	7.3 B	4.1 A
NT	20-40	153 A	79.3 B	6.0 B	5.8 B	13.7 B	8.7 A	1.6 B
CT		205 A	71.9 B	4.2 B	5.0 C	14.2 B	5.3 C	2.7 A
CV (%)		37,57	9.26	13.99	6.33	23.14	5.65	20.16

(1)Management systems: F: forest; NT: no-tillage; CT: conventional tillage. (2)Means followed by the same letter in each column for each layer did not differ statistically by the Tukey test at 5 %.

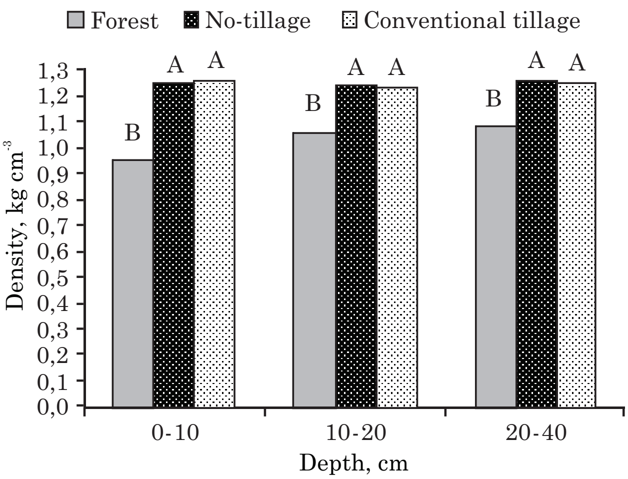

Figure 2. Variation in soil density as a function of management system and soil depth (p<0.05).

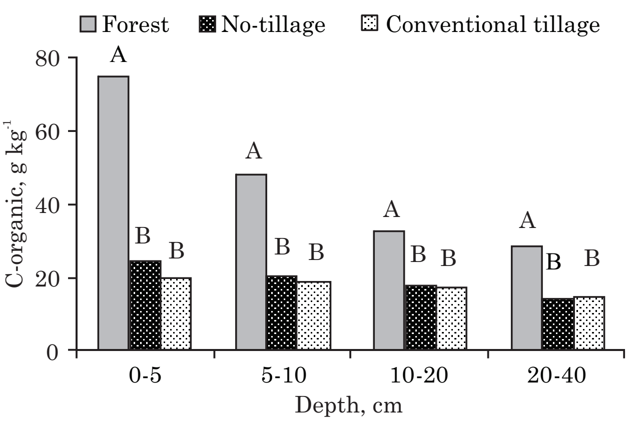

Figure 3. Total organic carbon (TOC) content as a function of management system and soil depth (p<0.05).

organic matter mineralization, which according to Castro Filho et al. (1998) and Calegari et al. (2006), causes a drop in TOC, impairing the quality of the organic matter and reducing the soil aggregate stability index. It can also be inferred that since the 0-5 cm layer is more susceptible to bad weather and above all human activity, becoming less aggregated, this could have been the cause.

The soil Ca^{2+} values (Table 4) and aggregation indicators (MWD, MGD and ASI) in the analyzed layers show the positive effect of Ca on aggregate stabilization. Similar results were obtained by Castro Filho et al. (1998). Although the values of dispersed clay (Table 4) indicate higher dispersion in the 5-10 cm layer, the result was not sufficient to reduce aggregate stability in this layer, as can be seen in table 2.

According to Castro Filho et al. (1998) and Calegari et al. (2006), this is the long-term result of liming, improving soil aggregation as a result of a rise in pH, infiltration and biological activity, in which mineralization products can lead to particle stabilization.

Tama & El-Swaify (1978) and El-Swaify (1980) ascribed the higher aggregation of Oxisols to positive charges in this soil, explaining the strong tendency toward kaolinite flocculation, resulting in the high flocculation observed (Table 4). This occurs because kaolinite has a lower zero point charge (ZPC) than the oxides and hydroxides of Fe and Al present in Oxisols. Kaolinite has a negative surface charge, whereas Fe and Al hydroxides are positively charged. This difference enhances flocculation, increasing soil aggregation through organic matter and functional organic groups.

Other explanations proposed the effects of polymerization of Al or fulvic acids to humic acids (Roth et al., 1991), and the calcium-induced formation of bonds between organic matter and clays (Castro Filho et al., 1998).

A reduction in the stability of macroaggregates and increased dispersed clay content were observed in the soil under CT (Tables 3 and 4). These results are in line with Oades (1984), who, assessing the effects of organic matter on the management and structural stability of soil, observed that these alterations were more concentrated in intensively farmed soils.

The accumulation of plant residues on the soil surface (0-5cm) under NT (Table 5) had beneficial effects on the soil physical and chemical properties, as the results of aggregation show. This is in line with Lal (1975), Blevins et al. (1977), Castro Filho et al. (1998), Beutler et al. (2001) and Calegari et al. (2006).

Silva & Mielniczuk (1998), assessing the aggregation of soils affected by agricultural use, observed that dystroferric Red Oxisols with higher levels of oxides, clay and organic C have a better structure than others with lower levels. This explains the high stability indices found in our study, even for conventional tillage, varying between 60.62 and 71.19 %, in the analyzed layers (Table 2). Oliveira et al. (1996) also ascribed this to the mineral composition of the clay fraction, considering gibbsite as the main factor responsible for higher aggregate stability. In contrast, Desphande et al. (1964) and Reichert et al. (1993) concluded that in soils containing iron oxides (Red Oxisols) no soil particle cementing effect occurs since these oxides are in discrete crystal form. Soils containing aluminum oxide, on the other hand, form interstratifications with clay minerals, acting as cement and aggregating soil particles, contradicting the aggregation results obtained in our study.

In terms of soil density (Figure 2), the fact that we found no significant differences between NT and CT, in line with Albuquerque et al. (1995) and Tavares Filho et al. (2001), can be attributed to the cumulative

Table 5. Average total organic carbon (TOC) contents under the management systems no-tillage (NT) and conventional tillage (CT) in the analyzed layers

Management system	Depth			
	0-5	5-10	10-20	20-40
	cm			
NT	23.5 A[1]	19.4 A	17.1 A	13.7 A
CT	18.5 B	17.9 A	16.1 A	10.2 A
CV(%)	7.34	8.30	9.74	18.3

[1]Means followed by the same letter in each column for each layer did not differ by the Tukey test at 1 %.

effects of agricultural traffic (tractors, harvesters, etc.) for 21 years continually under NT in the study area, which could explain these results. According to Roth et al. (1991), the most dense aggregates have a higher consistency due to the intense traffic, resulting in lower susceptibility to destruction by trapped air. On the other hand, this effect imposes no restrictions to crop development, as demonstrated by Calegari et al. (2006), Llanillo et al., 2006, Ferreira et al., 2010 and Tavares Filho & Tessier (2010). According to Roth & Pavan (1991), the clay in Red Oxisols plays a minor role in expansion and contraction, which is why the compaction induced by machinery and tractor wheels during preparation can accumulate over time, resulting in high soil density.

Although the soil density under native forest (F) was lower, the aggregate stability indicators were higher, probably due to the higher content of organic C that plays a role in forming and stabilizing aggregates. According to Tisdall & Oades (1982), organic polymers are bonded to inorganic surfaces by polyvalent cations and hydroxymetal polymers, stabilizing the larger aggregates and facilitating the assembly of aggregate classes with a diameter between 1.00 and 0.50 mm, forming larger aggregates.

It is worth remembering that these agents are destroyed by cropping, by which larger aggregates are broken down into smaller units. Oades & Waters (1991) attributed the aggregation of particles of < 0.25 mm with aggregates of > 2.00 mm to the aggregating effect of roots and hyphae of vesicular-arbuscular mycorrhizal fungi that interact with clay particles and silt by means of mucilages producing high-stability aggregates. This is also a reason why aggregates between 0.50 and < 0.25 mm (Table 3) are present in lower quantities and evenly distributed at varying depths in areas under no-tillage and forest in comparison with areas under conventional tillage. Tisdall & Oades (1982) attribute the higher quantity of aggregates of <1 mm in areas under crops to the fact that they are stable to rapid wetting. In addition, no-tillage soil has a higher average of larger water-stable aggregates (8-4 mm) than the CT system (Table 3). These results are in line with the positive correlation between organic C and aggregate classes with an average size between > 8 and 2-1 mm, and with the work of Da Ros et al. (1997), Castro Filho et al. (1998) and Beutler et al. (2001), who observed higher values for aggregates of > 2 mm with increasing organic matter contents in the soil.

In contrast, water-stable aggregates under conventional tillage are concentrated in lower size classes (0.50 to < 0.25 mm). This is in part due to intensive soil preparation by agricultural machinery which breaks down larger aggregates into smaller units and also to the possible oxidation of organic C, indicated by the lower organic C content in this management system (Table 5). This was confirmed by comparing conventional tillage with no-tillage, in which the less intensive use of agricultural machinery and maintenance of plant cover protects the soil from aggregate breakdown by rainfall. Similar results were reported for Red Oxisol by Carpenedo & Mielniczuk (1990), Calegari et al. (2006), Llanillo et al. (2006), Ferreira et al. (2010) and Tavares Filho & Tessier (2010).

Therefore, with regard to the recovery of the soil physical characteristics, the no-tillage system proved advantageous over conventional tillage. Studies at varying soil depths showed that the soil properties, e.g., aggregation indicators and aggregate classes, are changed in different ways by the same management system.

It is therefore important to point out that recovering the structural stability of degraded areas using no-tillage must be combined with other factors, such as maintaining a constant soil cover, crop rotation and soil management practices under adequate moisture conditions.

CONCLUSION

Increasing soil disturbance (F < NT < CT) results in a reduction of soil stability, measured in terms of the stability indicators analyzed (MWD, MGD, ASI, distribution of aggregate classes, WDC, and FI), which proved valid for studies of soil aggregation.

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